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SHORT CONTRIBUTION

A simple parameterization for ice sheet ablation rate[1]

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ABSTRACT

A parameterization of monthly mean ice sheet ablation as a function only of surface air temperature and insolation is examined. By considering differences in summer climate between the present and the last ice age, it is suggested that the parameterization adequately describes long-term changes in ablation. Although significant discrepancies are found between the parameterization and the seasonal variation of ablation observed on present-day glaciers, the seasonal ablation cycle is still predicted accurately enough to maintain the validity of the parameterization for long-term net annual variations.

1. Introduction

Several recent models of northern hemispheric ice sheet fluctuations during the last $\sim 10^6$ years have used relatively simple parameterizations of ablation on the ice sheet surfaces (Weertman, 1976; Sergin, 1979; Pollard et al., 1980). The process of ablation is an important part of the climatic control over the size of present-day glaciers, and ablation variations in the past could have been important in controlling the past ice sheet fluctuations. Ablation is used here to mean "the reduction in mass of a vertical ice sheet column due to the removal of H_2O out of the column by surface processes"; calving into oceans is excluded. In practice ablation mostly involves melting and subsequent runoff in surface or basal streams during summer, but can also involve evaporation or wind-drifting. The full process is complex and is described in Paterson (1969, Ch. 4) and Sugden and John (1976, Ch. 14).

In Pollard et al. (1980) the monthly mean ablation, A, at any point on the ice sheet surface is parameterized in the form

$$A = \max[0; aT + bQ + c] \qquad (1)$$

where T is the monthly mean surface air temperature (corrected for ice sheet elevation above sea-level using a constant atmospheric lapse rate), Q is the monthly mean insolation at the top of the atmosphere, and a, b, and c are constants. For non-zero A, (1) is basically a linearized energy-balance equation for a melting surface with no heat capacity; somewhat more complex parameterizations involving more climatic variables were first developed in the glaciological literature (e.g., Sverdrup, 1935). Of course more sophisticated snowmelt models are in current use, and a few have recently been applied to paleoglaciological problems (e.g. Williams, 1979).

This note examines the adequacy of such a simple parameterization as (1) for ice age models. In Section 2 past ablation variations for a given month (July) are considered, and found to be adequately describable in terms of T alone. However ablation typically has a large non-linear seasonal variation and is negligible in winter, making it important to "choose" the right months of the year to compare with past eras, i.e., to correctly predict the beginning and end of the main ablation season. In Section 3 some discrepancies are found between present-day seasonal observations and a parameterization of the same type as (1), but the scatter is only equivalent to a relatively small error ($\sim \pm 1$ month) in the phase of the seasonal ablation cycle. The purpose of including Q in (1) and the numerical values for a, b and c are discussed in Section 4.

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2. Variations in past eras

Ablation depends not only on surface air temperature and insolation but also on cloud cover, wind speed, relative humidity and on physical properties of the surface itself. Each of these parameters has probably varied systematically over synoptic scales in past eras and so could potentially be important for ice age ablation parameterizations. One approach of estimating the relative importance of the meteorological parameters (cf Coakley, 1977) is shown in Table 1. The Δp values in column 2 represent differences in the parameter p between the present July and July 18 Kyear BP on continents around ~50° N, estimated from the GCM results of Gates (1976). These summer values are the most relevant to the net annual ablation, since by far the most ablation occurs in the summer months. The values of the partial derivatives $\partial A/\partial p$ in column 3 are estimated from the theoretical "free ablation" graphs of Kraus (1975), and represent the regions of these graphs in which the bulk of ablation occurs on real glaciers (i.e., by melting with air temperature $\gtrsim 0$ °C); these values are consistent with earlier semi-empirical ablation formulae (e.g., Sverdrup, 1935). They are calculated for a standard glacier surface (with albedo 0.5) in "steady-state" ablation, i.e., with no sensible heat storages and with all ablated water removed immediately. [The partial derivatives for T and Q correspond to a and b in (1), and their values are considered further in Sections 3 and 4.]

The magnitudes of the products in column 4 indicate that by far the largest ablation rate changes of past eras have been caused by the changes in surface air temperature, T. This suggests that a parameterization in terms of T alone would be adequate for an ice age model; (actually the next most important variable, surface wind speed, could not realistically be predicted in simple one-layer climate models).

It should be noted that the Δp values in Table 1 are averages over many days, but the steady-state partial derivatives take no account of the pronounced non-linear daily cycles involved in real ablation situations. However in situations where melting is occurring for a significant fraction f of each day, one would expect that the inclusion of these day–night effects would reduce the products in column 4 by factors of between ~f and ~1, and would not seriously affect their relative magnitudes.

Table 1 also neglects any systematic changes in properties of the ice sheets themselves. For instance sub-zero internal temperatures can cause meltwater to refreeze elsewhere in the ice sheet and not run off; the winter cold-wave of seasonal heat in near-surface layers can significantly inhibit ablation (Muller, 1963). There is little or no direct evidence of such systematic changes as ice sheet size varied in the past, but these properties do vary widely on

Table 1. *Effect of past variations Δp of summer climate on ablation rate A*

Parameter p	Δp (ice age July minus present July)	$\partial A/\partial p$ in (g cm^{-2} month^{-1} per units of col. 1)	Δp $(\partial A/\delta p)$ in (g cm^{-2} month^{-1})
Surface air temperature, T (°C)	−10	15	−150
Insolation, Q (W m^{-2})	±15*	(0.8) × (0.4) = 0.32†	±5
Total cloudiness (areal fraction)	+0.2	Effect of sunlight absorbed:	
		(0.8) × (−70) = −56†	−11
		Effect of net IR:	
		(−0.8) × (−80) = 64‡	+13
Surface wind speed (m s^{-1})	+2	15	+30
Relative humidity (%)	+10 (at 800 mb level)	1	+10

* Representative not of July 18 Kyears BP but of the general magnitude of past variations in mean summer insolation at ~50° N due to the orbital perturbations (e.g., Vernekar, 1972).

† Factor of (0.8) represents ablation per sunlight absorbed by the glacier surface (Kraus, 1975); factors of (0.4) and (−70) represent changes in sunlight absorbed per change in the relevant parameter p as computed by Schneider and Dickinson (1976, table 1) allowing for multiple reflections between cloud deck and surface.

‡ Factor of (−0.8) represents ablation per net infrared radiation lost by the glacier surface to the atmosphere (Kraus, 1975); factor of (−80) represents an average sensitivity of this infrared loss to various types of cloud cover as determined by glacial field measurements (Wallen, 1948; Lister and Taylor, 1961).

present glaciers and ice caps (Paterson, 1969, Ch. 2). Such properties can be predicted only by relatively complex ice sheet models, and are effectively assumed constant in most simple ice age simulations.

3. Present-day observations

In this century considerable glaciological fieldwork has been devoted to relating the ablation on glaciers and ice caps to the local meteorological conditions (e.g., Paterson, 1969, Ch. 4). Schytt (1967) and Loewe (1971) among others have compiled sets of present-day glacial data and plotted ablation rate, A, against surface air temperature, T, averaged through most or all of the ablation season, i.e., ~May to ~September. (Insignificant ablation occurs in winter months outside of the ablation season.) For interannual variations on individual glaciers, the relationship is good and shows $\partial A/\partial T \sim 10$ (g cm^{-2} month^{-1}) per (°C); however there is considerable scatter between glaciers in different types of climates (e.g., continental versus maritime), and also between measurements averaged only over a few weeks or less on the same glacier. Much of this scatter in the relationship between A and T is probably due to seasonal and latitudinal variations of insolation and also due to variations in surface albedo, which can change seasonally from ~0.8 (fresh snow) to ~0.5 (melting ice) (e.g., Wallén, 1948). These variations would correspond to ablation rate variations of ~100 g cm^{-2} month^{-1} in column 4 of Table 1.

In Fig. 1 we have attempted to improve the ablation parameterization by adding a second variable "net radiation absorbed", R, which primarily contains the effects of insolation, surface albedo and also cloudiness. As far as an accurate representation of this data is concerned, the result shown is basically negative; the considerable scatter in the relationship between A and T has been reduced only slightly if at all by the addition of the second variable R. The scatter in the figure must be due to some combination of observational error, seasonal and interglacial variability of ice body properties such as seasonal heat storage and refreezing, and also due to the exaggerated point-to-point variability of surface wind speed and relative humidity for measurements averaged only over a few days. Unfortunately even if these effects were resolvable from the available data, a realistic treatment of these variables (and also of seasonally varying surface albedo contained in the variable R) is beyond the scope of most simple ice age models.

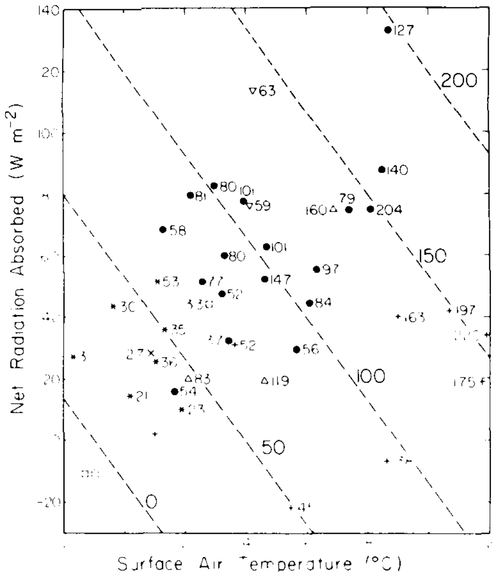

Fig. 1. Measurements of present-day ablation vs surface air temperature, T, and net solar and infrared radiation absorbed, R. Values adjacent to each point are ablation rates, A, in g cm^{-2} month^{-1}. The measurements are averaged over a whole number of days during the ablation season. The figure contains all the data we found where simultaneous determinations of daily mean A, T, and R were published. The general level of observational error for each variable (not often reported) may be $\lesssim$10% of the total range in the figure. The sources for the various points in the figure are: ● Kårsa Glacier (Wallén, 1948); + Hoffells. Glacier (Ahlmann and Thorarinsson, 1938); • Isaschen. Ice Cap (Sverdrup, 1935); △ Sveanor Snowfield (Sverdrup, 1935); ▽ Britannia Glacier (Lister and Taylor, 1961); × Barnes Ice Cap (Ward and Orvig, 1953); □ Kessel. Snowfield (Ambach and Hoinkes, 1963). The dashed lines of constant ablation rate show a "fit" that corresponds to the parameterization in the text.

The level of scatter from the linear fit in Fig. 1 is $\lesssim\pm 50$ g cm^{-2} month^{-1}. This is equivalent to $\sim\pm 5$ °C in air temperature, which is much less than the full seasonal variation at any one location and is comparable to the change through one month in spring or autumn. Therefore the beginning and end of the main ablation season could be predicted to within ~1 month by a parameterization in terms of T alone, with a non-linear cutoff below $T \lesssim -5\,^\circ\mathrm{C}$ to represent negligible ablation in winter.

4. Parameterization

Although the radiative variable R has not eliminated the scatter in Fig. 1, it still seems preferable to include the seasonal variation of Q in an ablation parameterization for the following reason: with all other variables held constant, the full winter–summer variation of Q would certainly affect ablation as much as a variation in T of ~10°C, and so the inclusion of Q should slightly improve the predicted phase of the seasonal cycle.

Numerical values for (1) are chosen below, but one should note that these values are constrained only within wide limits by the data in this paper, and the main point is the basic form of (1). As in Table 1, we estimate $\partial A/\partial Q$ ~0.3 (g cm^{-2} month^{-1}) per (W m^{-2}). (This steady-state derivative should be affected only slightly by day–night effects since the daily cycle of insolation is roughly correlated with that of ablation.) Using the value of $\partial A/\partial T$ from present-day interannual variations (Section 3), this yields the following equation for monthly mean quantities:

$$A\ (\mathrm{g\,cm^{-2}\,month^{-1}}) \approx \max[0;\ 10T\ (^\circ\mathrm{C}) + 0.3Q\ (\mathrm{W\,m^{-2}}) - 50] \qquad (2)$$

We have estimated the constant "50" in (2) by comparison with the data in Fig. 1, using R (W m^{-2}) = $0.4Q - 80$. [The factor 0.4 allows for multiple reflections off a ~0.3 cloud cover (Schneider and Dickinson, 1976), and 80 W m^{-2} represents net infrared loss from a melting surface with this cloud cover (Lister and Taylor, 1961).] The corresponding linear fit is shown in the figure. This constant "50" in (2) is also consistent with the general observation that significant ablation occurs only where the monthly mean temperature rises much above ~−7 °C in summer (e.g., Orvig, 1954; Bull and Carnein, 1968). The non-linear cutoff in (2), basically due to the transition from melting to evaporation, corresponds to the non-linear temperature dependence (roughly T^2 to T^3) suggested by Ahlmann (1948).

In summary, one should expect significant discrepancies between eq. (2) and present observed seasonal cycles of ablation. Much of this discrepancy could be due to seasonal variations of surface albedo, but Fig. 1 shows that other factors (e.g., seasonal heat storage) are significant. However, any such seasonal discrepancy should not be serious for the ice age problem as long as the summer months during which most ablation occurs are predicted reasonably well. This is because Table 1 shows that for these months the past variations of ablation rate have been controlled by past variations of surface air temperature, consistent with eq. (2).

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